

COMPARING THE EFFECTIVENESS OF THREE ACOUSTIC EMISSION PROCEDURES FOR PREDICTING STRENGTHS OF FINGER-JOINTS FROM TROPICAL AFRICAN HARDWOODS

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ABSTRACT

*Stress at first acoustic emission event-count, as well as cumulative event-count at 80 percent of mean failure stress and cumulative event-count at 80 percent of mean proportional limit stress were separately regressed on strengths of finger-joints from Obeche (*Triplochiton scleroxylon*), Makore (*Tieghemella heckelii*) and Moabi (*Baillonella toxisperma*). The regression suggested that all the three acoustic emission properties could be used to non-destructively predict the ultimate tensile and bending strengths of finger-joints from the three hardwoods. However, stress at first event-count seemed most suitable for predicting ultimate tensile strength of finger-joints from the three species, whilst cumulative event-count at 80 percent of mean failure stress seemed best for modulus of rupture. Correlation coefficients obtained for the prediction models developed were, generally, good and statistically significant ($\alpha = 0.05$).*

Keywords: Acoustic emission, ultimate tensile strength, modulus of rupture, tropical hardwoods

INTRODUCTION

Classic static tests are considered as more desirable evaluation methods for the mechanical properties of structural timber. However, these tests are difficult to perform and are time consuming. Fast, reliable and easy-to-use methods for predicting the properties of structural timber will not only offset the above difficulty, but also go a long way to promote the efficient utilisation of timber. Non-destructive wood testing permits wood properties of individual timber pieces determined destructively to be correlated with properties measured non-destructively in order to assign property values without damage due to overloading, thereby improving the efficiency of timber utilization (Bodig and Jayne, 1982).

This paper assesses and compares the effectiveness of using three acoustic emission procedures for non-destructively predicting ultimate tensile and bending strengths of finger-joints from three tropical African hardwoods.

Acoustic Emissions

When mechanical stress is applied to any material, be it a pure crystal or heterogeneous composite, intermittent generation of low amplitude stress waves created by sudden increases in defect size may be detected (Rice and Skaar, 1990; DeBias *et al.*, 1996). The term acoustic emission (AE) refers to the elastic waves produced by deformation and failure processes occurring in stressed materials. AE is said to be a popular non-destructive material testing technique (Rice and Skaar, 1990). The

strain energy or stress wave released is, in most cases, caused by a shift in a local defect area, sometimes called micro-checks, and arises from local stress concentrations in non-homogenous materials (DeBias *et al.*, 1996). The most common method of reporting AE activity is to describe the count rate or cumulative event-counts as a function of the stress applied to the material (Rice and Skaar, 1990).

There have been several attempts at using the technique to evaluate the strength of adhesive bonds (Porter, 1964; Pollock, 1971). Pollock (1971) reported that specimens with poor adhesion had a higher emission rate than those with good adhesion, and begun to emit at lower stress levels. A study was conducted on how to use AE to predict failure of 50 mm x 150 mm Douglas fir finger-joints and showed how the method could be used as a non-destructive testing method for wood (Dedhia and Wood, 1980). The study indicated that ultimate bending strength could be predicted to within 1.8% to 25% depending on the load at which the prediction was made and the nature of the finger-joint.

MATERIALS AND METHODS

Materials

Test specimens were prepared from wood samples of Obeche (*Triplochiton scleroxylon*) of mean density of 351 kg/m³, Makore (*Tieghemella heckelii*) of mean density of 677 kg/m³ and Moabi (*Baillonella toxisperma*) of mean density of 819 kg/m³, imported from West Africa. One cubic meter samples of each species were randomly collected from three logs of each species for the study. Finger joints were prepared from three

profile types, F1, F2 and F3 (Table 1 and Figure 1) using defect-free straight-grained wood samples of each species. The specimens were matched on the basis of their modulus of elasticity before jointing. The joints were glued with resorcinol formaldehyde glue (DIANOL 33N) and end-pressed using three different pressures, P1, P2 and P3 (Table 2). The adhesive was double spread on the specimens before pressing, and the specimens were cured at a temperature of 30°C for about 48 hours. The specimens were cut to tension test specimen dimensions of 15 x 70 x 700 mm for Makore and Moabi, and 15 x 58 x 700 mm for Obeche. For the bending test, however, specimen dimensions were 21 x 70 x 2000 mm for Makore and Moabi, and 21 x 58 x 2000 mm for Obeche. Test specimens were conditioned to 10% moisture content before testing.

Static Tension Test

The tension specimens were tested using a servo-controlled fatigue test machine (SHIMADZU SERVOPULSER EHF-ED 10/TD1) with a static loading capacity of 100 kN. A cross-head speed of 3 mm/min was used and failure occurred within 5 to 10 minutes. Each specimen was tested in accordance with ASTM D 198-84 (1994). Specimens were set up so that the finger-joint was in the middle between the grips. Elongation was measured using two strain gauge-type transducers of resolution of 500 x 10⁻⁶ / mm set over a distance of 80 mm with the finger-joint positioned in the middle. Ten replications of finger-jointed specimens were tested for each combination of finger profile and end pressure for each species. This resulted in 90 specimens for each species.

Table 1: Finger profile parameters

Type of joint	Length L (mm)	Pitch p (mm)	Tip width t (mm)	Slope of Fingers θ	Relative joint area ($2L/p$)	% cross section reduction ($100t/p$)
F1	10	3.7	0.6	1 in 6	5.5	16.2
F2	18	3.7	0.6	1 in 12	9.7	16.2
F3	20	6.0	0.6	3 in 20	6.7	10.0

Refer to Figure 1

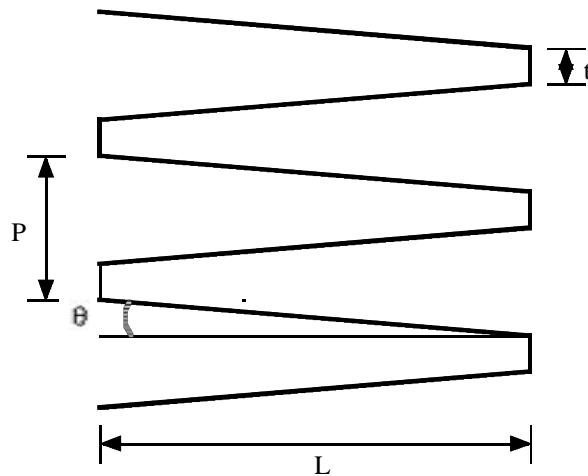


Figure 1: Finger profile parameters

Table 2: Applied end pressures (MPa)

End Pressure	Timber Species					
	Moabi and Makore			Obeche		
	F1	F2	F3	F1	F2	F3
P1		8		4	4	2
P2		12		8	8	3
P3		18		12	12	4

Static Bending Test

The bending specimens were tested using an INSTRON TCM 10000 test machine with a static loading capacity of 100 kN. Cross-head speeds of 20 mm/min (for Makore and Moabi) and 5 mm/min (for Obeche) were chosen, and failure occurred within 3 to 5 minutes. Each specimen was tested flat-wise, under a four-point loading arrangement in accordance with the ASTM D 198-84 (1994) and the Japanese Industrial Standards, JIS Z 2101 (1970). The distance between the loads was 350 mm and the shear span was 650 mm. The specimen was positioned on the supports such that the finger-joint was at the centre of the 1 m span. Deflection of the shear-free zone was measured using two strain gauge-type transducers of resolution of 500×10^{-6} / mm positioned on either side of the finger-joint. Ten replications of finger-jointed specimens were tested for each combination of finger profile and end pressure for each species. This resulted in 90 specimens for each species.

Recording of Acoustic Emissions

Two AE sensors were attached to each face of the test specimens 25 mm apart on each side of the finger-joint, with the aid of silicon adhesive and rubber bands. Signals received by the AE sensors were pre-amplified to 40 dB and further amplified by a main amplifier in the AE Analyzer to 20 dB.

Threshold level was 50 mV. This threshold was just above the noise level at the beginning of the test, and thus eliminated the possibility of introducing emission signals arising from a changing background noise level. The AE Analyzer used was the SHIMADZU SAE-1000A, equipped with band filters, which received, filtered and cumulatively counted the amplified signals. The filters were set between 100 kHz (High Pass Filter) and 500 kHz (Low Pass Filter). All signals outside this band were attenuated. Loads were also channeled through a strain amplifier to the AE Analyzer. The digital signals from the counter were converted to analog form and both loads and counts were sent to a personal computer for analysis. A schematic diagram of the AE test set-up for the bending specimen is shown in Figure 2.

Regression Analyses

An analysis of variance (ANOVA) performed using the F-test at 5% significant level, showed that, generally within each finger profile, differences in end pressures were not statistically significant with respect to finger-joint MOR and UTS. In an attempt to increase sample sizes for the analyses, all the data collected from the statistically similar end pressures were combined for each finger profile type for each species. Data considered to be outliers were omitted.

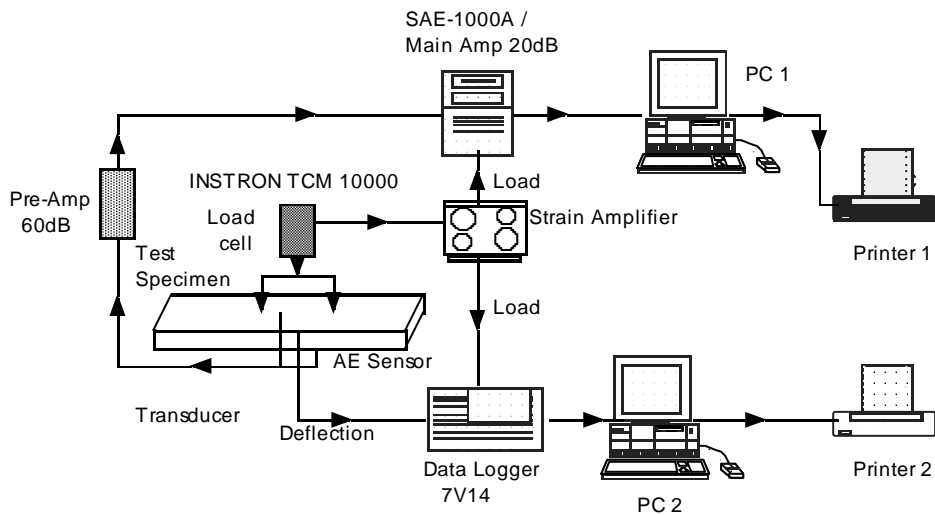


Figure 2: Schematic diagram of the Acoustic Emission test set-up for the bending specimen

Selection of Stress Levels for Predicting Strengths

Porter *et al.* (1972) reported that load level just beyond the proportional limit should permit estimates of failure load accurate to within $\pm 10\%$. It is also reported that joint strength could be estimated at 80% of failure load to within $\pm 7\%$ (Dedhia and Wood, 1980). A study has also shown that bending proof loads of 60, 70, 80 and 90 percent of the expected ultimate strength did not significantly reduce the strength of end-jointed Douglas fir (Strickler *et al.*, 1970). These authors also indicated that the accuracy of predicting finger-joint strength reduces, the further away from the ultimate failure load the prediction is made.

The mean proportional limit stresses in tension for finger-joints made from Obeche, Makore and Moabi were 67%, 46% and 46% respectively of the mean failure stresses and 67%, 75% and 76% respectively of the mean failure stresses for bending. As non-destructive prediction method, low stress levels, which would not cause incipient failure in the finger-joints and subsequently lead to failure in service, were targeted. Stresses as low as 80% of mean proportional limit stress, and 80% of mean failure stress were therefore chosen for predicting the finger-joint strengths.

A graph of applied stress versus cumulative event-counts was drawn for each specimen (Figure 3). For most of the specimens the number of counts increased exponentially with applied stress. Those that deviated from this curve were excluded from

subsequent regression analyses. From this curve two sets of ultimate strength versus cumulative event-count data were collected for each specimen. These sets corresponded to readings of ultimate strength and cumulative event-count at 80 percent of mean failure stress (designated by N_m) and also ultimate strength and cumulative event-

count at 80 percent of mean proportional limit stress (designated by N_p) for each specimen. An additional set of ultimate strength versus stress at first event-count (designated by f_1) data was also read for each specimen as the third procedure for predicting strength.

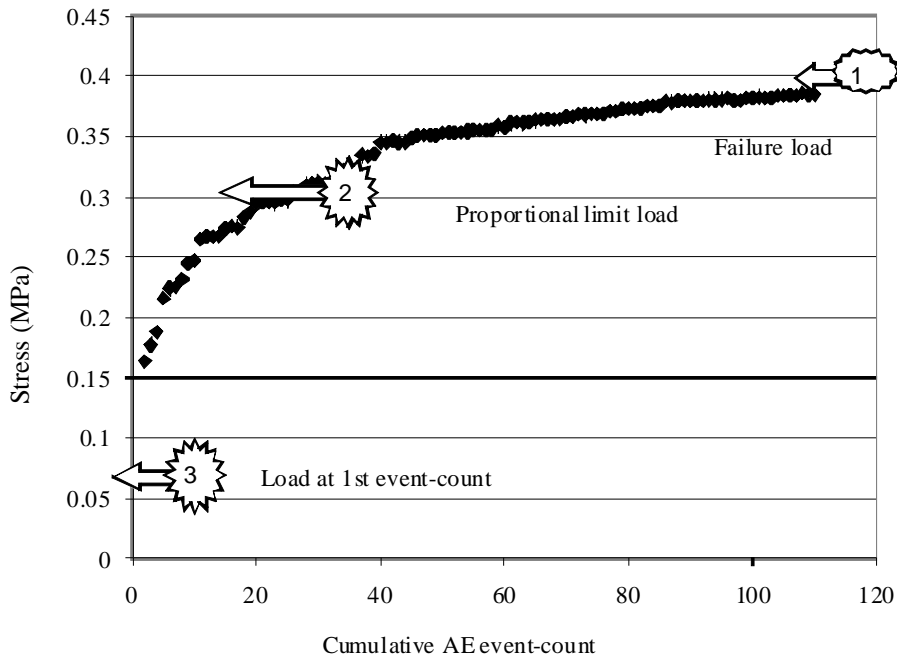


Figure 3: Applied tensile stress versus cumulative acoustic emission event-counts curve for typical Obecbe finger-jointed specimen

Using least squares regression analysis, the best fitting linear or logarithmic functions between ultimate strength (in bending and tensile) and N_p , N_m and f_1 were separately determined for each finger profile type and for the combined data of all profiles of each species. The regression models used were of the form,

Linear functions:

$$f = \beta_0 + \beta_1 f_1 + \varepsilon_0 \quad (1)$$

Logarithmic function:

$$f = \beta_2 + \beta_3 \ln(N) + \varepsilon_1 \quad (2)$$

Where, f = ultimate strength (UTS or MOR) of specimen (MPa)

N = cumulative event-count at 80% of mean failure stress (N_m) or 80% of mean proportional limit stress (N_p)

f_1 = stress at first event-count (MPa)

β_0 , β_1 , β_2 , and β_3 = regression coefficients

ε_0 and ε_1 = residual errors

RESULTS AND DISCUSSION

Regression diagrams for the combined data of the three profile types of each species were presented for the linear and the logarithmic regression functions for each prediction method in Figures 4 to 6.

Predicting UTS and MOR from the three Acoustic Emission Parameters

The regression results (Figure 4) showed negative correlation between UTS as well as between MOR

and cumulative event-counts at 80 percent of mean failure stress (N_m). Negative correlation was obtained for the regression of each profile type and for the combined data from the three profile types of each species. Similar trend of results were also obtained for the regressions of UTS as well as MOR on cumulative event-counts at 80 percent of mean proportional limit stress (N_p) (Figure 5). Thus as N_m or N_p increased, UTS and MOR decreased, seemingly indicating that specimens emitting higher N_m may have lower strength than those emitting lower N_m which confirmed earlier studies (Pollock, 1971).

The linear regressions of UTS as well as MOR on stress at first event-count (f_1) (Figure 6) gave positive correlation coefficients. Positive correlation coefficients were obtained for the individual profile types and for the combined data from the three profile types. Thus as f_1 increased UTS and MOR also increased, seemingly indicating that strong specimens began to emit acoustic waves at higher stress levels than weak ones, in agreement with Pollock (1971). For the tension test (Figure 6), correlation coefficients obtained for the combined data under the prediction using stress at first AE event count procedure f_1 , of 0.57, 0.63 and 0.64 for Obeche, Makore and Moabi respectively, appeared generally higher than those obtained for the predictions using N_m and N_p , (Figures 4 and 5) indicating that predicting UTS from f_1 was the best among the three prediction methods. As a non-destructive method, predicting strength from stress at first event-count would be much preferred since it gives assurance that low levels of stress which would not initiate failure in the finger-joints leading to failure in service, were applied. For the bending test (Figure 6), correlation coefficient obtained for the combined data under the prediction, were comparatively lower than those obtained using N_m and N_p (Figures 4 and 5), except for the case of Obeche ($r = 0.63$), suggesting that N_m and N_p have some advantage over f_1 for

predicting finger-joint MOR. The mean strength properties obtained for the specimens of the different profiles showed that finger-joints from profile F2 began to emit acoustic waves at comparatively higher tensile stress levels of about 17, 19 and 10 MPa for Obeche, Makore and Moabi respectively than those from profiles F1 of about 10, 6 and 4 MPa respectively, and from profile F3 of about 10, 9 and 7 MPa respectively. In bending, however, there were only little differences between the stress levels for finger-joints from the three profiles for Makore and Moabi. The results also indicated that finger-joints from Obeche began emitting AE stress waves at the highest stress levels in tension (of 34% of ultimate stress) and in bending (of 37% of ultimate stress) compared with Makore (14% and 21% respectively) and Moabi (17% and 22% respectively). This indicates that finger-joints from Obeche were the most efficient among the three species, in agreement with Ayarkwa *et al.* (2000a and 2000b).

Higher correlation coefficients were also obtained for the prediction model using N_m than that using N_p which agrees with Porter *et al.* (1972) and Dedhia and Wood (1980) who reported that the accuracy of predicting finger-joint strength from AE event-counts reduces, the further away from the failure load the prediction is made.

Significance of the Prediction Models

Correlation coefficients obtained for the regression of UTS as well as MOR on N_m , N_p and f_l were generally not very high. However, the range of correlation coefficients obtained were comparatively higher than those obtained for the regressions of static tension MOE on UTS of 0.04, 0.25 and 0.07 for the same specimens of Obeche, Makore and Moabi respectively (Ayarkwa *et al.*, 2001). The correlation coefficients obtained under the three AE prediction procedures were again comparatively higher than those obtained for the

regression of static bending MOE on MOR of 0.64, 0.17 and 0.05 for Obeche, Makore and Moabi respectively (Ayarkwa *et al.*, 2001). These results suggest a stronger relationship between UTS as well as MOR on N_m , N_p and f_l than between the same strength properties and their MOEs obtained from static tests. This indicates that the acoustic emission technique for non-destructive prediction of UTS and MOR for finger-joints of the African hardwoods (Obeche, Makore and Moabi) is more efficient than using the static testing method of regressing MOE on MOR.

The test of significance of the regression models, at 5% significance level, showed for the combined data of the three finger profiles studied for each species that, all the regression models were statistically significant. For the individual profile types, for both the tension and the bending tests, most of the regression models developed were also statistically significant.

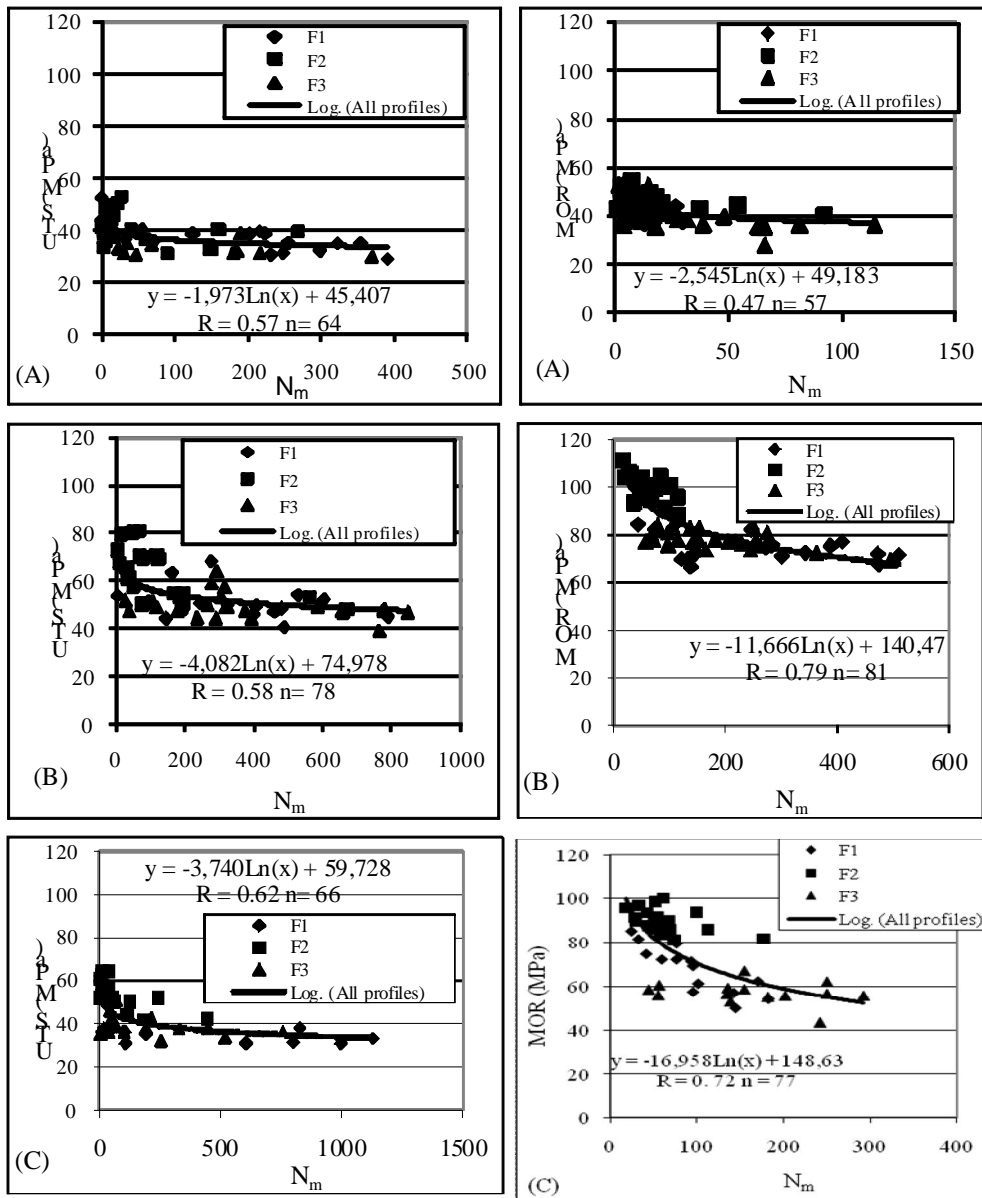


Figure 4: Regression of ultimate tensile strength (UTS) and modulus of rupture (MOR) on cumulative acoustic emission event-count at 80% of mean failure stress (N_m) for finger-joints from Obeche (A), Makore (B) and Moabi (C)

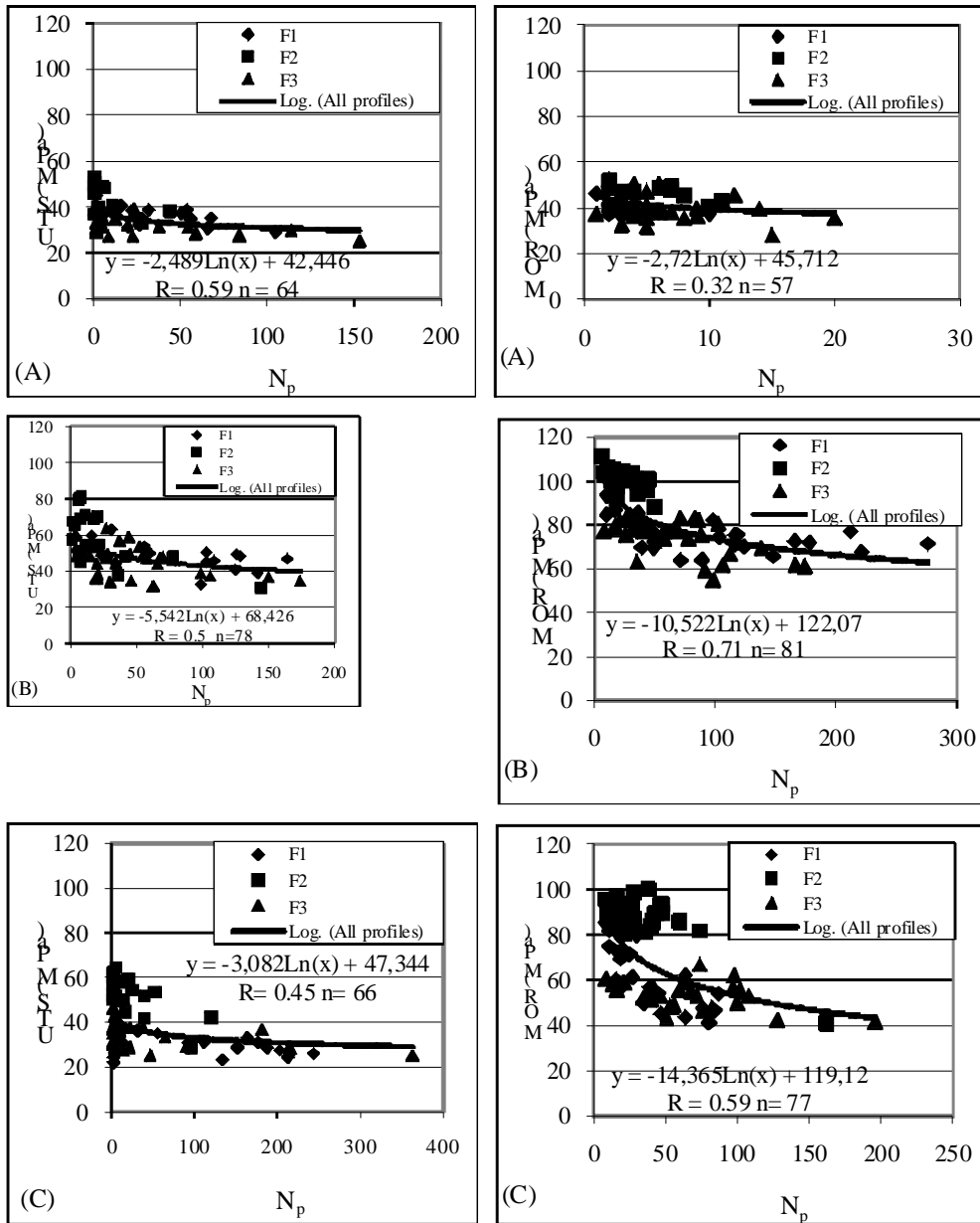


Figure 5: Regression of ultimate tensile strength (UTS) and modulus of rupture (MOR) on cumulative acoustic emission event-count at 80% of mean proportional limit stress (N_p) for finger-joints from Obeche (A), Makore (B) and Moabi (C).

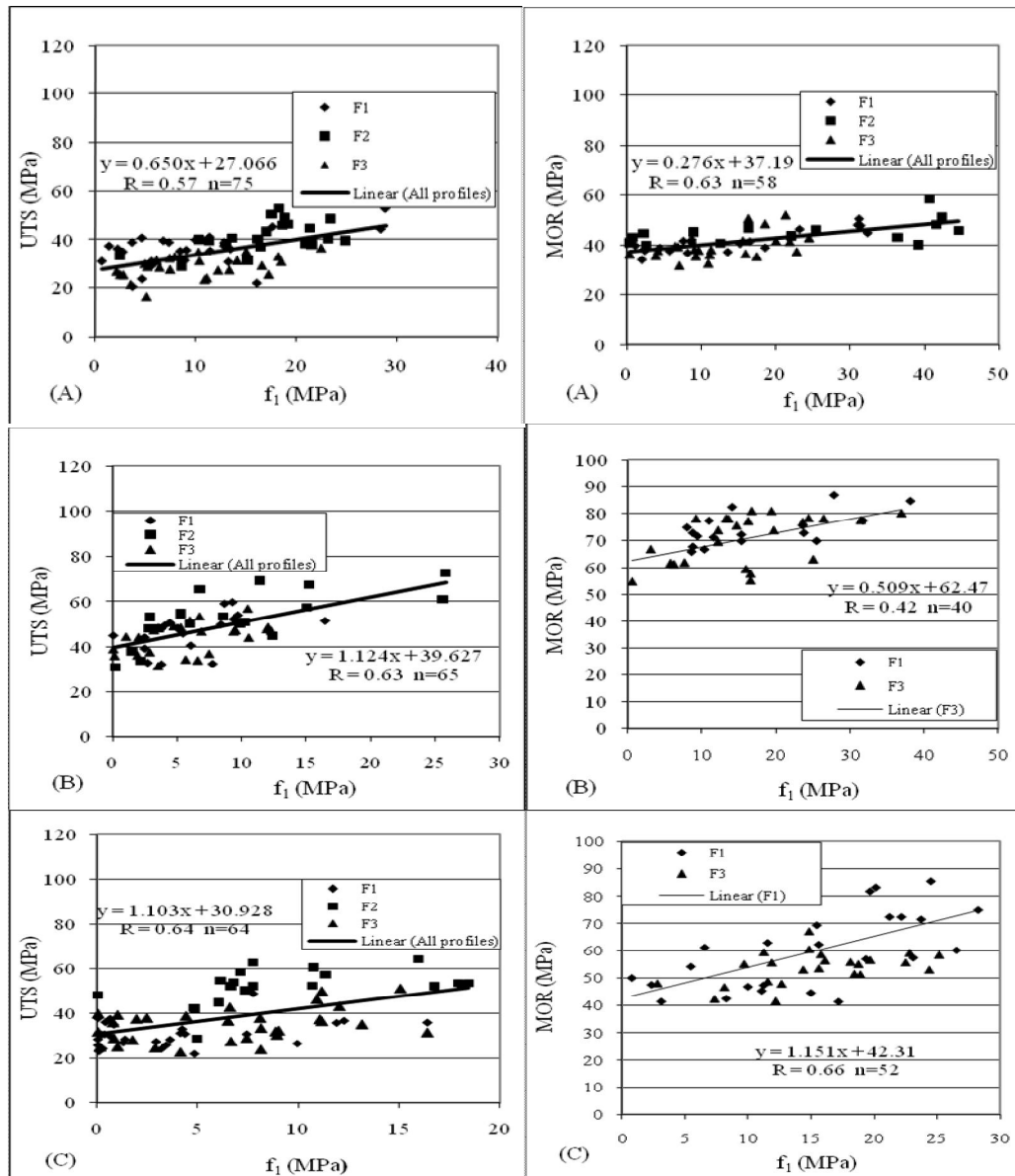


Figure 6: Regression of ultimate tensile strength (UTS) and modulus of rupture (MOR) on stress at first acoustic emission event-count (f_1) for finger-joints from Obeche (A), Makore (B) and Moabi (C).

CONCLUSIONS

Results led to the conclusion that the correlation of cumulative acoustic emission event-counts as well as the stress at first acoustic emission event-count to ultimate tensile strength and modulus of rupture could non-destructively predict these properties of the finger-joints. Prediction models developed were generally statistically significant, and the correlation coefficients obtained for the regression of ultimate tensile strength and modulus of rupture on the acoustic emission properties were also reasonable for the finger-jointed specimens.

Prediction of ultimate tensile strength of finger-joints from stress at first event-count seemed the best among the three methods studied, as it resulted in generally the highest correlation coefficients. Predicting modulus of rupture from cumulative AE event-counts at 80 percent of mean failure stress was also the best among the three prediction methods. All the three prediction methods could adequately predict ultimate strength of finger-joints from the different finger profiles studied for the three species.

The acoustic emission technique seems to hold great prospects as a non-destructive testing method for predicting tensile and bending strengths of finger-joints from the three tropical African hardwoods.

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